Chapter 1

Project Overview

1.1 Mission

The mission of the Muon $g-2$ experiment at Fermilab and its context in the High Energy Physics program have been officially summarized in excerpts from the DOE Mission Need Statement [1] approved in September 2012.

> The primary mission of the DOE Office of High Energy Physics (HEP) is to understand the universe at its most fundamental level through the study of matter and energy, space and time, and the forces governing basic interactions. The Standard Model of particle physics documents the current status of that understanding, which is known to be both stunningly robust, yet necessarily incomplete. An urgent mission of the particle physics community is to complete the Model. The tools required include high-energy colliders, which can directly produce the highest mass particles, and high-intensity accelerators, which can tease out the tiny effects of still unknown interactions in the data through high precision.
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> One of the more persistent hints of new physics has been the deviation between the measured muon anomalous magnetic moment, $a_\mu = (g-2)/2$, and its Standard Model expectation, where both are determined to a precision of 0.5 parts per million. This fundamental measurement has been pursued for decades with increasing precision. The discrepancy has been interpreted to point toward several attractive candidates for Standard Model extensions: supersymmetry, extra dimensions, or a dark matter candidate. The Large Hadron Collider (LHC) is now delivering on its promise to explore physics at the highest mass ranges to date, although no new physics has yet been found. A new and more precise muon $g-2$ experiment offers a strategic opportunity to search for new physics through alternative means, which could lead to a fuller and more coherent picture of the underlying physics.
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> The search for new physics can be carried out in complementary ways on the different frontiers of particle physics. The measurement of the muon anomalous magnetic moment is sensitive to interactions at the TeV scale, which is also the scale probed by the LHC. The capability gap filled by the new muon $g-2$ experiment derives from the ability of the measurement to elucidate the underlying

> physics we hope to discover at the LHC and probe areas of the newly discovered physics that are inaccessible to the LHC experiments.
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> The current muon $g-2$ measurement is used as a benchmark for new physics and has been used as input into the parameter space explored in almost all model dependent searches for new physics at the LHC, but the current discrepancy between the muon $g-2$ measurement and the theoretical prediction could be explained as a statistical fluctuation at the three-sigma level and has only been observed by one experiment. If the discrepancy is false, then this will cause serious confusion in interpreting LHC results. The discrepancy needs to be confirmed and established above the accepted discovery threshold of five standard deviations above a fluctuation.
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> Should LHC discover new physics at the TeV scale and the $g-2$ discrepancy is confirmed, a precise determination of $g-2$ is expected to provide direct measurements of the coupling constants of the new particles responsible for the discrepancy, fundamental parameters of the underlying theory and a window on the underlying symmetries of the new physics. In many cases, it is expected that these parameters will not be measured with adequate precision at the LHC alone.
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> There are no facilities, equipment, or services currently existing or being acquired within the Department of Energy, other government agencies, public organizations, private entities or international bodies that are sufficient to address these gaps.

The goal of the Muon $g-2$ experiment at Fermilab is a four-fold improvement in the experimental precision thereby reducing the error on a_μ to 140 ppb. If the discrepancy measured in E821 is truly an indication of new physics, then the difference with the current theoretical prediction will exceed the 5σ discovery threshold. Obtaining this precision requires observation of the muon spin precession with more than 20 times the statistics of the BNL E821 experiment while controlling systematics at the 100 ppb level.

1.2 Muon $g-2$ Project Scope

The scope of the Muon $g-2$ project can be easily visualized by looking at the work breakdown structures (WBS) shown in Figures 1.1 and 1.2.[1] Outside of the management portions, the project is divided into three major areas encompassing the accelerator modifications, storage ring, and detectors. The disassembly and transport of E821 equipment, now complete, has also been costed as part of the project. By agreement with DOE OHEP, the disassembly and transport proceeded as an OPC cost in advance of the schedule of CD reviews. A very substantial amount of the scope with the detector WBS is being funded via an NSF MRI which was awarded in mid-2013, a DOE Early Career Grant to Brendan Casey, or an in-kind contribution from INFN collaborators. The division of scope among the various funding sources is described in detail in the Detector Scope Document, GM2-DocDB-1313. However,

[1] Figures 1.1 and 1.2 also show the organization chart and institutional responsibilities at the time of writing the TDR.

the full scope appears in the DOE Project's resource loaded schedule of activities and is managed as a unified project, with all risks documented and controlled through the project office and progress toward the deliverables tracked using the Fermilab EVMS.

1.2.1 Accelerator (WBS 476.2)

The accelerator portion of the project includes the upgrades and modifications required to convert the existing antiproton complex at Fermilab into a muon source and deliver a high-purity beam of 3.1 GeV/c muons to the Muon $g-2$ experiment. A number of common accelerator components are needed for both the $g-2$ and Mu2e projects. These elements have been pulled out of both projects in order to better facilitate management of these components to simultaneously meet the specifications and schedule demands of both experiments. These common elements and their current status are discussed in Section 1.3.2. A brief description of the accelerator improvements required solely for $g-2$, corresponding to each L3 area in the WBS, is given in the list below.

- **Target Station (WBS 476.2.2)** The AP0 target hall, formerly used for antiproton production, will be utilized for the production of the muon beam. Protons from the Booster with 8 GeV kinetic energy will impact a target immediately upstream of a Li lens. The target and lens are the same as those used for the antiproton production. The Li lens has to be pulsed at a lower gradient, but higher repetition rate, thus requiring some modifications to the power supply. Pions with a momentum around 3.1 GeV/c are focussed by the Li lens and directed out of the target hall through a 3 degree bend created by a single-turn pulsed magnet (PMAG). Protons that pass through the target are deposited in a water-cooled beam dump which requires replacement due to a leak that developed near the end of Tevatron operation.

- **Beamline (WBS 476.2.3)** The beamline portion of the WBS includes all modifications required to a multitude of beamlines. Starting with the primary proton beam before it impacts the target, the final focussing quadrupole needs to be replaced with a triplet to provide more flexibility in focussing the protons into a smaller spot-size on the production target. When the pion beam emerges from the target vault, it is captured into a new high-density FODO lattice that provides a better muon capture efficiency by tripling the number of quadrupoles currently in the line. The muon beam is then brought through another section of beamline and injected into the Delivery Ring, formerly called the Debuncher. The muons are circulated a few times around the Delivery Ring to allow protons to separate by time-of-flight before an abort kicker is fired to remove the protons.[2] The muons are then extracted from the Delivery Ring and brought through a new section of beamline connecting to the g-2 storage ring.

- **Controls and Instrumentations (WBS 476.2.4)** Standard accelerator control systems and interlocks will be required for beam delivery to the experiment. New instrumentation will be required in the new beamlines and instrumentation in existing

[2]The injection into the Delivery Ring and the abort system are also needed by Mu2e to inject 8 GeV protons into the Delivery Ring and provide a safe beam abort, therefore these systems are part of the general accelerator improvements discussed in the next section.

portions of the accelerator complex will require modification due to the relatively low intensity of the pulsed muon beam. Safety systems including interlocks in the beamlines and the controls to the MC-1 building, the new experimental hall housing the storage ring, are also included in this area.

1.2.2 Ring (WBS 476.3)

The ring portion of the WBS includes all of the preparations needed to reassemble and install the E821 $g-2$ storage ring at Fermilab and connect it to a new cryogenic plant that will be constructed from Tevatron refrigerators.[3] A number of subsystems associated with the injection and storage of the muon beam will be upgraded. Field monitoring equipment is an integral part of storage ring and poses one of the largest challenges to the experiment. The NMR systems and calibration procedures must be capable of determining the magnetic field to better than 100 ppb, with an ultimate goal of achieving a 70 ppb uncertainty on the average field acting on the stored muon population.

- **Magnet (WBS 476.3.2)** The storage ring magnet must be reassembled holding very tight tolerances, starting with the foundation of base plates and jacks, followed by installation of more than 700 tons of return yoke and the superconducting coils. A total of 72 pole pieces line the top and bottom of the magnet gap and must then be installed with even tighter tolerances. Vacuum systems for the superconducting coils will be newly-provided since the older E821 equipment was absorbed into the RHIC complex.

- **Inflector (WBS 476.3.3)** The old inflector from E821 is currently used as the default plan for injecting into the storage ring. Reinstallation of the old inflector requires new vacuum systems and a connection to the cryogenic plant through the existing lead pot. However, an alternative inflector is still considered a technical opportunity, which would both mitigate a risk of delay to the project (if the old inflector fails to turn on or fails during commissioning) and also improve the muon yield. A new inflector with a larger opening and less material across the beam channel would allow for a better match into the storage ring, thus reducing beam oscillations from the unmatched dispersion, and increase the storage efficiency by as much as a factor of four.

- **Storage Ring Vacuum (WBS 476.3.4)** The vacuum chambers will require some modifications to accommodate relocated NMR probes and *in vacuo* straw trackers. The chambers will be installed with vacuum equipment that is either newly-purchased or recycled from the Tevatron wherever possible.

- **Kickers (WBS 476.3.5)** The electromagnetic kickers that place the injected muon beam onto a central orbit are being redesigned to provide a more powerful kick while sustaining the increased repetition rate of the new $g-2$ experiment. A Blumlein design is the preferred option to produce a kick with the correct pulse-width along with sharp rise and fall times.

[3] The cryogenic plant is being constructed off-project as part of an overall plan to provide cryogens to both $g-2$ and Mu2e experimental halls.

- **Quadrupoles (WBS 476.3.6)** The quadrupole system is being upgraded to run the ring at a higher n value and provide a more massless quadrupole plate in the injection region where the muon beam has to pass.

- **Controls and Instrumentation (WBS 476.3.7)** The storage ring controls and instrumentation will need to be upgraded to be compatible with modern systems used at Fermilab. Instrumentation inside the superconducting coils will not be altered, but the read-out, monitoring, and controls all require updating.

- **Field (WBS 476.3.8)** The magnetic field portion of the WBS is disproportionately large compared to other level 3 areas due to the complexity associated with shimming the magnet to high uniformity and the many NMR systems required to determine the absolute field strength. A series of active and passive shimming techniques are used to produce an extremely uniform magnetic field when integrated azimuthally around the storage ring. In order to measure the field in the storage region, the NMR trolley from E821 will be reused with some minor upgrades. This device is pulled out of a garage every 2-3 days and travels around the ring making measurements of the field at the center of the magnet gap without ever having to break vacuum. In between trolley runs, a series of fixed NMR probes monitor the field changes at the edges of the storage volume to better interpolate field changes from one trolley run to the next. Finally, the NMR trolley must be absolutely calibrated in a region of the storage ring where the magnetic field has been shimmed with even higher uniformity. Plunging probes are used to determine the field at the location of the NMR trolley probes and are absolutely calibrated against a special, spherical probe that has been used for past muonium hyperfine and $g-2$ experiments. All of these NMR systems require updated readout and data acquisition systems.

1.2.3 Detector (WBS 476.4)

The detectors and electronics for the experiment will all be newly constructed to meet the demands of measuring the spin precession of the muon to a statistical error of 100 ppb, while controlling systematics on ω_a to the 70 ppb level. This is a substantial improvement over the E821 experiment, and better gain stability and corrections due to overlapping events in the calorimeters are crucial systematics addressed in the new design. A new tracking system will allow for better monitoring of the stored muon population, thus improving the convolution of the stored muon population with the magnetic field volume, and establishing corrections to ω_a that arise from the electric field and pitch corrections; see Section 4.4. The data acquisition must be able to handle the increased data rates and allow for the traditional T analysis of the data and the new Q method described in Section 16.1.2.

- **Calorimeters (WBS 476.4.2)** New calorimeters will be constructed using an array of PbF_2 crystals readout by SiPMs. Unlike in E821, where the calorimeters were read out as one monolithic block, the array of crystals will allow for spatial resolution of pileup. A stable voltage distribution is required to maintain the gain stability requirements, along with a calibration system capable of verifying that the stability requirements are being met.

- **Trackers (WBS 476.4.3)** New straw trackers will be installed at select positions inside the main ring vacuum chambers to allow precise reconstruction of the decay positrons. As with the calorimeters and any other materials close to the muon storage region, great care must be taken not to create any perturbations to the magnetic field. The trackers will be readout by ASDQ ASICs that provide amplification, shaping, and discrimination. The discriminated signals are digitized by a TDC implemented in a field-programmable gate array (FPGA). Also included is a collection of smaller, dedicated detectors that are installed around the storage ring. This category includes an entrance counter to mark the initial time when a muon bunch enters the ring, an extinction monitor to check for leakage protons between the muon bunches, and deployable fiber harp monitors within the storage ring. The fiber harps are strung with scintillating fibers and allow for a direct, but destructive, measurement of the distribution of stored muons and their associated beam dynamics parameters.

- **Backend Electronics (WBS 476.4.4)** Signals from the calorimeters will be digitized with new 800 MHz waveform digitizers which must be synchronized through a distributed clock system.

- **DAQ (WBS 476.4.5)** A new MIDAS-based data acquisition system will be developed to collect data from calorimeters and trackers, while also providing online monitoring of the data quality. For each injection of a muon bunch into the storage ring, the DAQ has to gather data from the various front-ends, package it through an event builder, and ship the data to mass storage for later offline analysis.

- **Slow Controls (WBS 476.4.6)** The slow controls system is new and encompasses an array of functionality including monitoring various environmental conditions to be stored and used if needed later for determining data quality, monitoring diagnostics for various subsystems, setting alarms to alert control room operators of problems, and providing automated controls to interface with various subsystems.

1.2.4 E821 Equipment Transfer (WBS 476.5)

The transport of the superconducting coils from Brookhaven to Fermilab was one of the highest risk elements of the project. In order to mitigate this risk as early as possible in the project timeline, the DOE authorized the equipment transfer to proceed on operating funds counted against the project TPC, but not part of the formal CD process. The transport has now been completed successfully, with all of the equipment which we are reusing from BNL E821 now on site at Fermilab.

1.3 Muon $g-2$ Dependencies Outside of the Project

In addition to the scope outlined in the previous section, there are a number of off-project components required for the success of Muon $g-2$ and the more global Fermilab program.

1.3.1 Proton Improvement Plan and NOvA Upgrades

The Proton Improvement Plan (PIP) at Fermilab is required to meet the demands of future proton economics and enable the 40 year old Linac and Booster machines to run reliably for another 20 years. Without this upgrade, the Booster can not reliably deliver the 9 Hz of beam required to feed the Main Injector for the NOvA program. Experiments like MicroBooNE (data in 2014), Muon $g-2$ (data in 2016), and Mu2e (data in 2019) all rely on an increase in the Booster repetition rate. The PIP is a staged set of improvements that eventually will increase the Booster to its maximum 15 Hz output. The Muon $g-2$ experiment requires 3 out of every 15 Booster batches that are then split into fourths and delivered at an average 12 Hz rate to the storage ring. Although the MicroBooNE experiment will be the first to suffer if the PIP goals are not recognized, it is important for these accelerator upgrades to stay on track in order to reduce conflicting beam demands since it is likely that MicroBooNE will continue to take data in parallel with Muon $g-2$. The Proton Improvement Plan is well underway with the Cockroft-Walton already replaced by a modern RFQ as an injector to the Linac, but the schedule has been affected by financial constraints.

Protons from the Booster need to be injected directly into the Recycler for $g-2$. This connection was recently completed as part of the NOvA project and will have been commissioned and in operation several years prior to the start of $g-2$. However, the kickers that enable the injection into the Recycler will have to operate at a higher repetition rate, but within their design specifications, for simultaneous operation of NOvA and $g-2$ (or eventually Mu2e). MicroBooNE directly uses the beam from the Booster and so does not place the same demands on injection into the Recycler.

1.3.2 The Muon Campus

The Muon $g-2$ and Mu2e experiments both reuse the anti-proton source to create individually customized muon sources. The initial plans that were developed independently for the experiments were fraught with conflicts. Over the last two years a plan has emerged to overcome those conflicts and replace them with synergies. Areas were identified where common equipment could be constructed to facilitate both experiments in a way that the overall cost of the muon program is minimized while compatibility is maximized. Furthermore, by treating the common pieces as more general civil construction and accelerator upgrades, the flexibility of the laboratory infrastructure increases and opportunities for future experiments beyond $g-2$ and Mu2e are enabled. In order to meet the combined specifications for $g-2$ and Mu2e, while also keeping an eye towards the future, these upgrades are separately managed in a series of General Plant Projects (GPPs) and Accelerator Improvement Projects (AIPs). The collection of upgrades has come to be known as the Muon Campus at Fermilab, and is broadly outlined in the list below.

- **MC-1 Building GPP:** This is the building that will house the $g-2$ storage ring in the high-bay, power supplies for large sections of the Muon $g-2$ and Mu2e beamlines in a central section, and the cryo facility for both experiments. This GPP is substantially complete, and we have received beneficial occupancy of the cryo room and the experimental hall.

- **Beamline Enclosure GPP:** This GPP provides a new tunnel to connect the former pbar source to provide beam to the MC-1 and Mu2e buildings.

- **Muon Campus Infrastructure GPP:** This GPP covers a few miscellaneous civil construction projects needed by both experiments including providing cooling for the He compressors reused from the Tevatron at the A0 building, an extension of the MI-52 building to provide room for extra power supplies and cooling skids, and possibly an additional electrical feeder.

- **Cryo Plant AIP:** This cryo plant will be constructed in the MC-1 Building reusing four refurbished refrigerators from the Tevatron to provide cooling to the Muon $g-2$ and Mu2e superconducting coils. The AIP is currently around 40% complete and installation in the MC-1 building has started.

- **Recycler RF AIP:** This AIP will add an RF system to the Recycler to allow protons from the Booster to be rebunched into the narrow ≈ 100 ns pulses needed for Muon $g-2$ and Mu2e.

- **Beam Transport AIP:** This AIP will create a new extraction kicker and connection from the Recycler to transport the primary proton beam to the Muon Campus.

- **Delivery Ring AIP:** This AIP will provide the common modifications needed to transform the pbar source into a delivery ring capable of providing muons to Muon $g-2$ and slow-spill protons to the Mu2e target.

  A more detailed description of the accelerator components can be found in Chapter 7 with a summary given in Table 7.7.

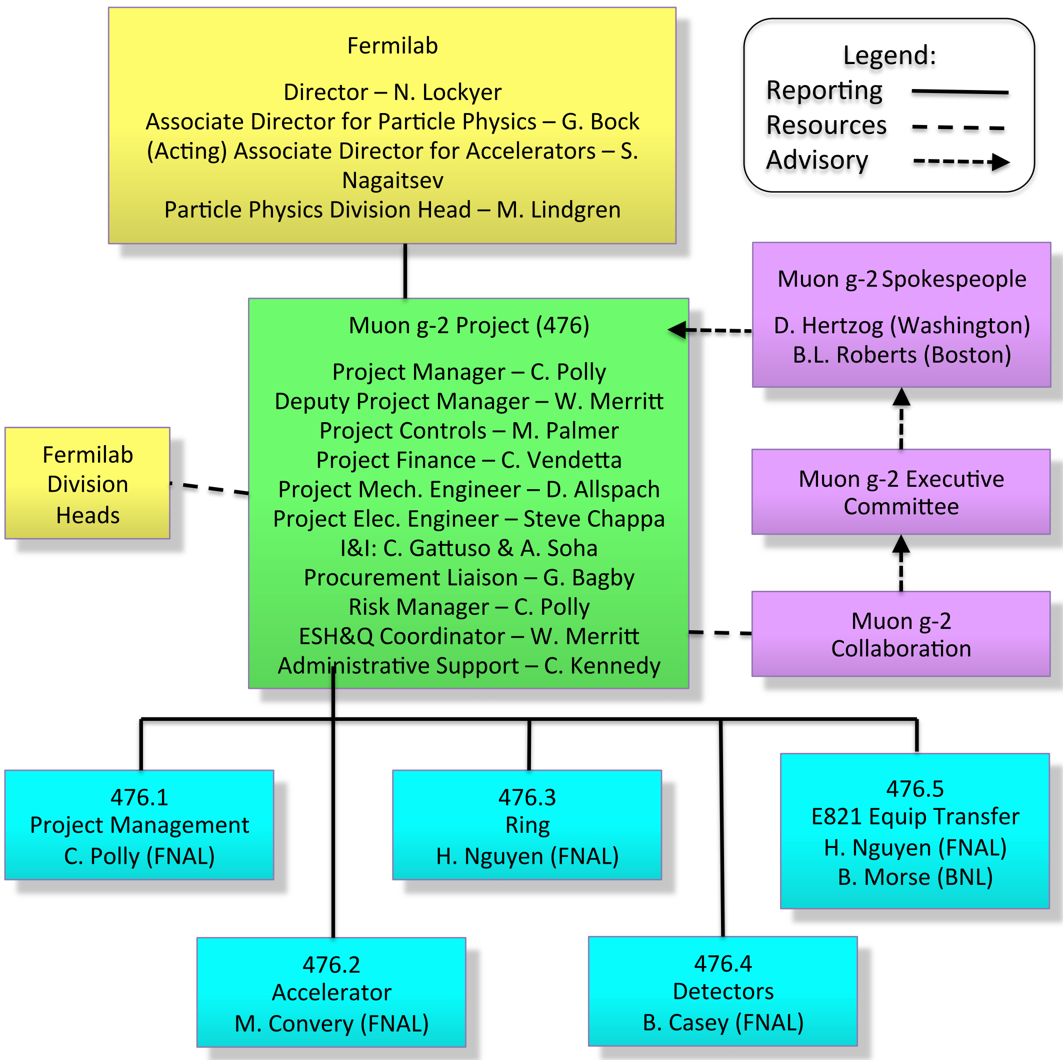


Figure 1.1: Organizational chart and WBS structure to Level 2.

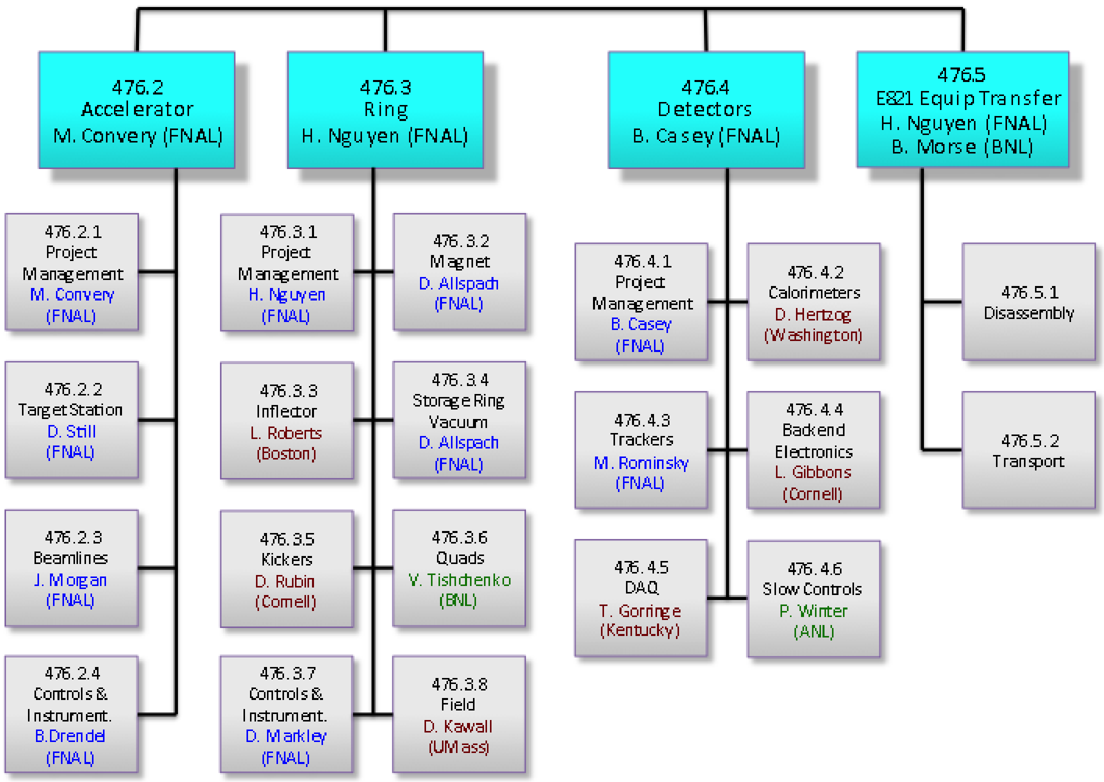
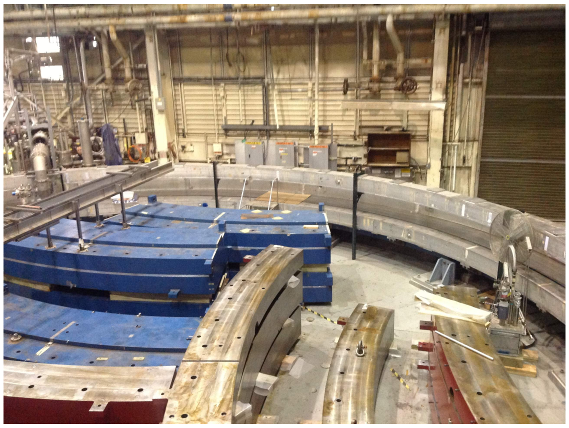


Figure 1.2: Organizational chart and WBS structure to Level 3.



(a) February 2013 disassembly at Brookhaven

(b) May 2013 yoke steel stored at Fermilab

(c) July 2013 storage ring arrives at Fermilab

Figure 1.3: Pictures of disassembly and transport showing (a) storage ring at Brookhaven in February 2013, (b) a large portion of the yoke steel stored at Fermilab in May 2013, and (c) the storage ring arriving at Fermilab in July 2013.

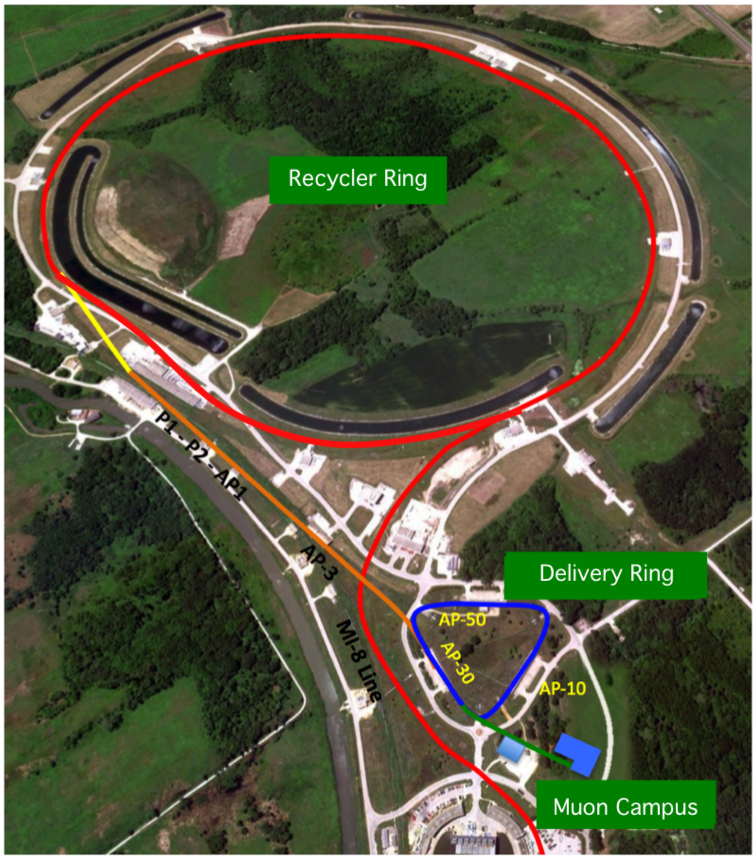


Figure 1.4: Aerial view of Muon Campus in relation to accelerator complex.

Figure 1.5: The completed MC-1 building in May 2014.

References

[1] http://science.energy.gov/hep/facilities/projects-missions-and-status/